Recent Developments in the Processing of P-type Spiral Drift Detectors

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***Abstract*-- Recently we have designed and developed various methods of fabricating a new P-type Drift Detector (PDD), which possesses one-sided hexagonal spiral shaped cathodes around the center anode. We have utilized gettering methods in order to remove detrimental impurities from the critical device-active area and transport them to a different part of the wafer. In this work, we discuss the intrinsic and the extrinsic gettering methods involved in the process. In the intrinsic gettering, we use the magnetic Czochralski silicon material that has a high resistivity (≥2kΩcm). This material naturally has high oxygen concentration (about $10^{18}/cm^3$), and under a high temperature cycling it provides nucleation sites where the impurities can precipitate. In the extrinsic process we utilize the phosphorus implantation to form a region with increased impurity solubility. The goal of these processes is to reduce the leakage current of the detector thus improving its energy resolution.**

I. Introduction

A new p-type, one-sided hexagonal spiral drift detector has recently been designed, simulated, constructed and tested [1]. This detector is intended as spectroscopic X-ray detector for extended X-ray absorption fine structure experiments (EXAFS) [2]. The existing electronics of EXAFS requires this drift detector to be made of P-type silicon. The signal in this detector is generated by transporting holes from the original position in the bulk, where they are generated by incoming radiation, to the anode. The large array of drift cells forces a design with maximum of two bonds per cell. This design creates a drift field by the spiral-based voltage divider [3]. Further, the leakage current created at the depleted part of the detector surface must not flow onto the detector anode. This current is also collected without an external connection to the cell. The leakage current generated at the depleted surface is collected directly on the inner terminal of the divider.

Manuscript received Oct 29, 2004. This work was supported in part by the U.S. Department of Energy under Contract No. DE-AC02-98ch.

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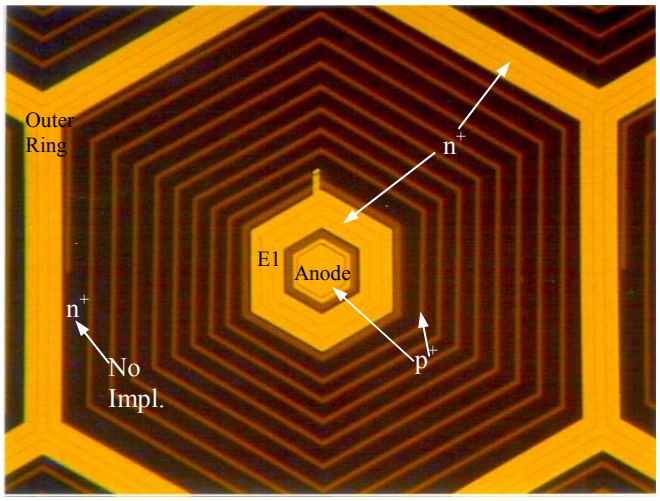

Fig. 1. The microphotograph of a drift cell with a hexagonal spiral structure.

Fig. 1 shows the microphotograph of the front side of a drift cell where the different regions are visible. The regions of boron look orange-red, while yellow aluminum covers the phosphorus implants in the outer and in the inner hexagonal frames, and the boron implant in the central anode. The dark colored area is not implanted, since it is naturally n-type due to surface inversion created by the positive charges in the oxide. The largest hexagonal frame defines the overall size of the drift cell. The area is exactly 1 mm^2 to comply with the required density of the readout channels. It has a phosphorus implant that forms a rectifying junction on the p-type bulk. This junction is covered by aluminum and is in contact with outer junctions of all the adjacent cells. The bias can be applied to all the drift cells with a single bonded connection. The other contact to the drift field-generating electrode is the phosphorus implanted hexagonal frame around the anode of the detector. In order to apply a voltage to this electrode, we need an individual bond for each drift cell. The anodes of all cells have to be individually contacted as well, and therefore the system of drift cells requires twice as many bonds as a system of simple diode pads where only one connection per pad is needed. The highest positive voltage of the drift cell is applied at the outmost hexagonal frame called the outer ring. The conventional current flowing at the surface starts there and is removed at the aforementioned phosphorus hexagonal frame located around the anode (E1). The current is due to the flow

of electrons, which are entering the surface at the small hexagon and are removed at the outmost hexagonal frame.

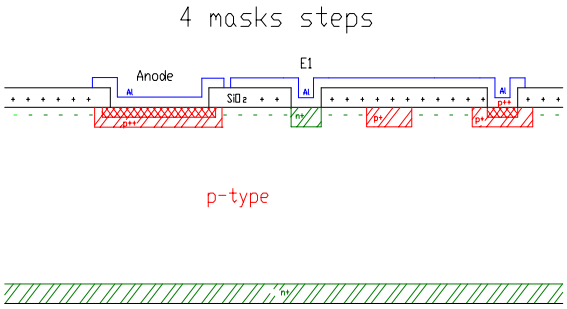

Fig. 2. The four masks processing steps.

The lithographic processes of the wafer are done on one side only, resulting in a simplified fabrication process. The radiation entrance side (backside) was uniformly implanted with phosphorus creating a shallow, rectifying n^+-p junction. Positive charges in the native oxide help to keep the thickness of the dead entrance layer at a minimum. Moreover, this layer is not sensitive to the radiation damage caused by very low energy X-rays that do not damage the silicon structure and produce only additional positive charges in the oxide. The four masks steps are shown in fig. 2. The design makes an active usage of the positive charge in the oxide as a rectifying junction on p-type silicon. The test results (Fig. 3) indicate that this device is operational. A typical americium spectrum can be recognized. Most of the X-ray peaks have been resolved. The deviation from the Gaussian shape of a few peaks, such as L_β and L_γ, is due to the presence of unresolved smaller peaks in their vicinity. The resolution of the detector is limited by the high leakage current (Fig. 4). We suspect that the impurities and the defects in the p-type material are the source of high leakage current. We are studying different gettering methods to modify the existing process steps that are needed to decrease the leakage current.

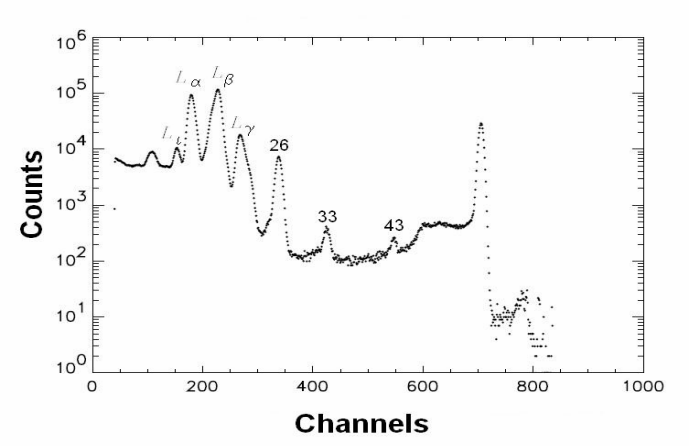

Fig. 3. An americium spectrum detected by a single hexagonal drift cell.

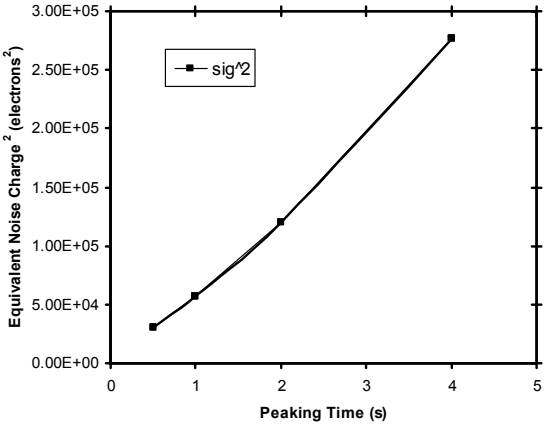

Fig. 4. Measured noise curve in equivalent noise charge (enc) square at room temperature for different peaking time of the shaper.

II. Leakage Current

In order to reduce the leakage current we need a detailed understanding of its origin.

Leakage current is made by sum of several contributions [4,5] and can be approximated as:

$$I_{leakage} = I_{depl} + I_{diff} + I_{surf} \qquad (1)$$

The first term is due to the generation of charge carriers in the depleted bulk. The second term is due to the generation of minority carriers in the quasineutral region, which diffuse into the depletion layer. The last term is due to generation at the surface of the depleted silicon.

Measurements on test structures produced on the same wafer as drift detectors indicate that in P-type drift detector, the generation of leakage current in the depleted bulk is the dominant term. The leakage current is proportional to the depleted volume V and inversely proportional to the generation lifetime τ.

$$I_{leakage} = I_{depl} = 0.5 q n_i V/\tau \qquad (2)$$

Here q is elementary charge, and n_i is the intrinsic carrier density.

The generation lifetime τ is inversely proportional to trapping density N_t of the unwanted impurities,

$$\tau = (\sigma \nu_{th} N_t)^{-1} \qquad (3)$$

where σ is the carriers' capture cross section, and ν_{th} is the thermal velocity of the carriers.

Therefore, the leakage current is directly proportional to the density of the unwanted impurities.

Now let's look at the magnitude of this density. To obtain leakage current equal to 4.8nA from 1cm^2 area of 0.4 mm thick detector equation (2) gives the generation lifetime τ equal 10ms. Therefore from equation (3), the trapping density of the unwanted impurities comes equal to 10^{10}/cm^3. The density of silicon atoms is $5x10^{22}$/cm^3. The ratio of atoms of unwanted impurities and the silicon atoms is $2x10^{-13}$. Therefore the unwanted impurities need to be $<<10^{-13}$, much less than part per trillion (PPT) or $<< 10^{-12}$, to obtain the leakage current less than 2nA from a detector area of 1cm^2 and 0.4 mm thick.

III. Gettering Method

Gettering is the process of removing impurities from the device-active area by transporting them to a preselected region of the wafer. Various gettering methods, such as intrinsic and extrinsic [6, 7, 8, 9], have been developed to meet the various technologic and economic demands of semiconductor device manufacturing. Intrinsic gettering is a controlled application of internal bulk oxygen atoms. They form the impurity sinks and leave a thin, defect-free region near the surface where the active devices reside. Extrinsic gettering is the method of forming a special layer with an increased impurity solubility on the backside of the wafer where the impurities will be transported. The gettering method is based on the fact that the most harmful impurities have high diffusivities at high temperatures.

To achieve a redistribution of impurities in a wafer these gettering methods utilize three different concepts [7, 8, 9]: 1) providing a predesigned region with preferred nucleation sites for precipitation ("relaxation-induced gettering"), 2) preparing a region with increased impurity solubility ("segregation-induced gettering"), or 3) injecting intrinsic point defects---like self-interstitials---into this region ("injection-induced gettering").

We create on the wafer simple diodes as parts of test structures where the leakage current, which defines the quality of the process, can be tested independently of any new features of the p-type drift detectors.

IV. Results and Discussions

A. Intrinsic Gettering

In order to maximize the effect of intrinsic gettering, during our process design, we use Magnetic Czochralski (MCZ) p-type silicon material with resistivity ≥2kΩcm. This material has a natural high oxygen concentration (about 10^{18}/cm^3). Under our three step temperature cycle (1100ºC for 6 hr, 700ºC for 16 hr, and 1000 º C for 5 hr) treatment during the oxidation process [10], it provides nucleation sites for impurities to precipitate. During the first high temperature step, the oxygen in the silicon is out-diffused to the surface silicon dioxide layer, which leaves a denuded zone beneath the surface where the device active region resides. During the second low temperature step, the remaining oxygen in the bulk of silicon starts slowly to nucleate, and forms a density of the nucleation sites. In the third high temperature step, these nucleation sites start to grow in size, while there is no change in the density of these nucleation sites. During the above mentioned temperature cycles, we believe the nucleation sites act like impurity sinks, and the impurities precipitate to those nucleation sites.

Fig. 5 shows a test result of leakage current for the Float Zone (FZ) p-type silicon material. This material has higher resistivity (8-10kΩcm), and naturally has less unwanted impurities. Fig. 6 shows the test result of leakage current for the MCZ p-type silicon material with ≥2kΩcm resistivity. Naturally it has more impurities than FZ material that we mentioned before.

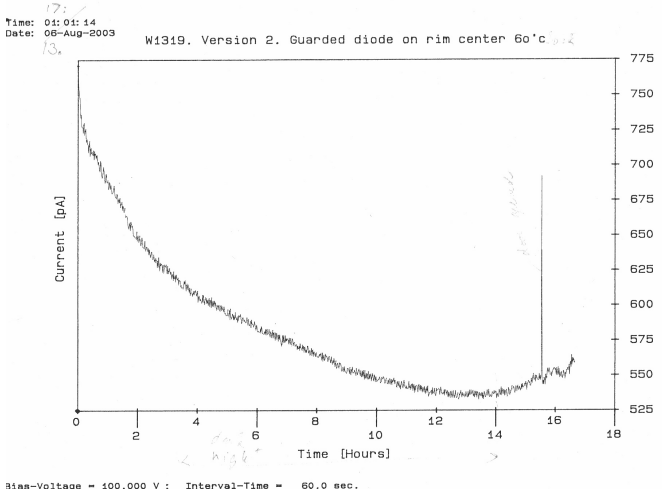

Fig. 5. Leakage current of single test diode verses time for FZ p-type silicon material with resistivity of 8-10kΩcm.

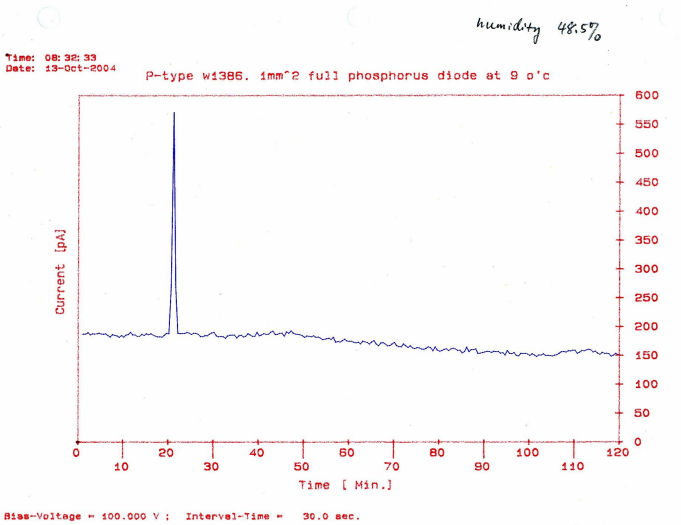

Fig. 6. Leakage current of single test diode verses time for MCZ silicon material with resistivity of 2kΩcm.

In spite of higher impurities in MCZ p-type silicon material, the results showed 3 times lower leakage current than FZ p-type material which has lower impurities to start with. It

proves our hypothesis that the high oxygen concentration in silicon forms impurity sinks under three temperature cycles. Intrinsic gettering is successful with MCZ material. However, one should be aware of the fact that oxygen can also be the thermal donor under certain, between 400ºC to 600ºC, temperature conditions.

B. Extrinsic Gettering

In our process of the PDD detector, the entire radiation entrance's side is implanted with phosphorus ions uniformly to form n^+-p junction. It is natural for us to think of using this phosphorus region as extrinsic gettering layer to transport detrimental impurities there. Originally the phosphorus implant was done in the last of four-mask steps. In this work though, the phosphorus implant was moved to the first process steps. Bare silicon wafer was implanted with phosphorus on one side prior to three temperature cycle of oxidation. The rest of the process steps are followed in the later sequence. In fig. 7 are shown the characteristics of a single test diode. It is produced by extrinsic gettering method using FZ p-type material. By comparing with the I-V characteristics showing on fig. 8 which was produced without extrinsic gettering, the extrinsic gettering didn't produce a better diode. It indicates that this method wasn't working under such phosphorus implant and under such temperature treatment.

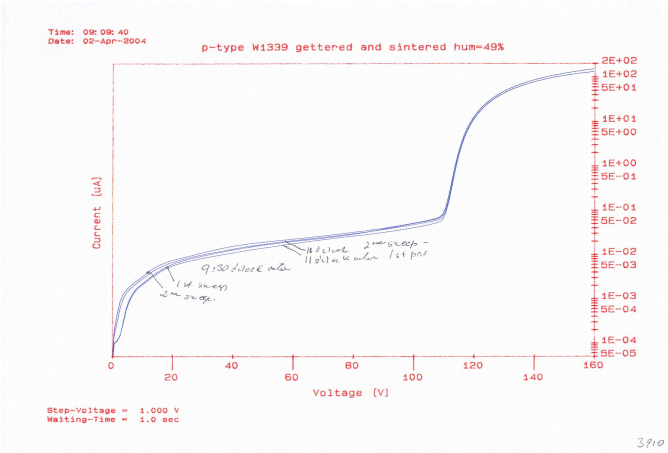

Fig. 7. The I-V characteristics of a single test diode which been produced by extrinsic gettering method.

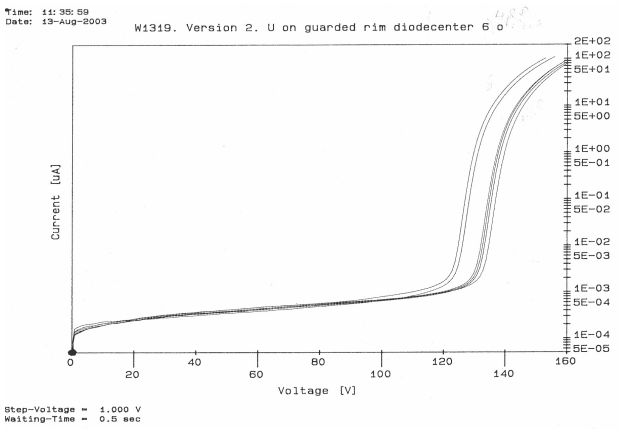

Fig. 8. The I-V characteristics of a single test diode which been produced without extrinsic gettering.

All the extrinsic gettering showing in the literature are all done on backside of the wafer which is ohmic contact side. Here our phosphorus implant (20keV & 50 keV; $8x10^{14}/cm^2$) side is n^+-p junction side. Therefore we have a more complicated situation in our hands. Also under three temperature step treatment, we believe that there is possibility that the impurities has been sent back to the bulk during the last high temperature step. Last it is also worth of our investigation for the suitable implantation energy and dose of phosphorus implantation. For example, the phosphorus dose can be increased to about $10^{16}/cm^2$.

V. Conclusions

Recently we have designed and developed various methods of fabricating a new PDD, which possesses one-sided hexagonal spiral shaped cathodes around the center anode. We have utilized gettering methods in order to remove detrimental impurities from the critical device-active area and transport them to a different part of the wafer. Therefore reduce the leakage current.

The intrinsic gettering on MCZ silicon wafer was successful due to the super-saturation of oxygen in MCZ p-type silicon. The oxygen nucleation sites, which formed by three temperature step treatment, act as impurity sinks. It leaves a denuded zone near the surface where the device active region resides. Nevertheless, by using current MCZ p-type silicon with ≥2kΩcm resistivity, the leakage current even after the intrinsic gettering has not yet reached the requirement of the EXAFS experiments. By using higher resistivity MCZ material we expect that it could further reduce the leakage current. During the detector process, a caution is needed to avoid oxygen becoming the thermal donor in the temperature range between 400ºC to 600ºC. Further test of detectors which were produced by intrinsic gettering method are underway.

Extrinsic gettering hasn't worked up to this point. We suspect that our phosphorus implant side is n^+-p junction side. It could make the problem more complicated. Also under three temperature step treatment, we believe that there is possibility that the impurities has been sent back to the bulk during the last high temperature step. We intend to modify our temperature step to one-temperature treatment. Finally it is also worth to investigate to find suitable energy and dose of phosphorus implantation.

VI. References

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